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Jeremy Decroix, Solène Kalénine

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What first drives visual attention during the recognition of object-directed actions? The role of kinematics and goal information

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1 **Title:** What first drives visual attention during the recognition of object-directed actions? The
2 role of kinematics and goal information.

3 **Author names:** Jérémy Decroix & Solène Kalénine

4 **Affiliations :** Univ. Lille, CNRS, CHU Lille, UMR 9193 - SCALab - Sciences Cognitives et
5 Sciences Affectives, F-59000 Lille, France

6 **Authors' adresse:**

7 Laboratoire SCALab UMR CNRS 9193

8 Université de Lille, SHS

9 Batiment A2 - Niveau forum +2

10 Domaine universitaire du Pont de Bois, BP 149

11 59653 Villeneuve d'Ascq Cedex, France

12

13 **Corresponding author:** Solène Kalénine

14 Mail: solene.kalenine@univ-lille.fr

15 Phone: +33 3 20 41 73 25

16

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1 **Abstract:** The recognition of others' object-directed actions is known to involve the decoding
2 of both the visual kinematics of the action and the action goal. Yet whether action recognition
3 is first guided by the processing of visual kinematics or by a prediction about the goal of the
4 actor remains debated. In order to provide experimental evidence to this issue, the present study
5 aimed at investigating whether visual attention would be preferentially captured by visual
6 kinematics or by action goal information when processing others' actions. In a visual search
7 task, participants were asked to find correct actions (e.g. drinking from glass) among distractor
8 actions. Distractors actions contained grip and/or goal violations and could therefore share the
9 correct goal and/or the correct grip with the target. The time course of fixation proportion on
10 each distractor action has been taken as an indicator of visual attention allocation. Results show
11 that visual attention is first captured by the distractor action with similar goal. Then the
12 withdrawal of visual attention from the action distractor with similar goal suggests a later
13 attentional capture by the action distractor with similar grip. Overall, results are in line with
14 predictive approaches of action understanding, which assume that observers first make a
15 prediction about the actor's goal before verifying this prediction using the visual kinematics of
16 the action.

17 Key-words: visual attention, predictive approaches, action semantics, object-directed action,
18 eyetracking

19

20 Word count : 217

1 Actions are complex cognitive phenomena and can be described at different levels of
2 abstraction, from abstract action intentions to the description of the mechanistic properties of
3 movements (Jacob & Jeannerod, 2005; Kilner, 2011; Urgesi, Candidi, & Avenanti, 2014).
4 Decades of research on action planning have highlighted the hierarchical structure of actions,
5 where higher-goals lead to the selection of sub-goals that are then translated into appropriate
6 motor programs (Cooper, Ruh, & Mareschal, 2014; Thill, Caligiore, Borghi, Ziemke, &
7 Baldassarre, 2013; van Elk, van Schie, & Bekkering, 2014; Wolpert, Doya, & Kawato, 2003).
8 Actions are thus organized and goal-directed movements.

9 Actions are not only planned around goals, but they are also perceived as goal-directed. Thus,
10 humans most likely identify their own actions and the actions of others as goal-directed (Hrkač,
11 Wurm, & Schubotz, 2014; Novack, Wakefield, & Goldin-Meadow, 2016; Vallacher & Wegner,
12 1987, 2012; Zacks, Tversky, & Iyer, 2001). Many pieces of evidence in this direction can be
13 found in the visual attention literature. During the observation of reach and grasp movements,
14 both children and adults make proactive gaze movements towards the expected landing point
15 of the action (Ambrosini, Costantini, & Sinigaglia, 2011; Flanagan & Johansson, 2003;
16 Flanagan, Rotman, Reichelt, & Johansson, 2013; Geangu, Senna, Croci, & Turati, 2015), which
17 suggests that observers do not simply follow the movement course as it unravels but predict
18 and anticipate the goal of the action. This bias of interpreting actions as goal-directed seems to
19 arise quite early in development. Infants are indeed able to track others' goals (Buresh &
20 Woodward, 2007) and they show a renewal of attention when an actress stops her movement
21 without achieving her goal (Baldwin, Baird, Saylor, & Clark, 2001). Overall, these data
22 highlight the importance of goals during the perception and the recognition of actions
23 performed by others (Ocampo & Kritikos, 2011).

24 Yet the decoding of action goals may be less straightforward during the perception of others'
25 actions than during action planning. Indeed, the actor's goal is not readily available for the

1 observer, and different approaches have been proposed to explain how one succeeds to
2 understand others' goals. Thus, sensorimotor approaches of action understanding have
3 suggested that goals "become "*visible*" in the surface flow of agents' motions" (Ansuini,
4 Cavallo, Bertone, & Becchio, 2014 p.1), that is, the actor's goal emerges in the mind of the
5 observer from the processing of the visual kinematics (i.e., reach trajectory, grip configuration
6 or means; cf. Grafton & Hamilton, 2007) of his/her actions. Several pieces of evidence suggest
7 that this ability may arise in development through repetitive association between movements
8 and their perceptual consequences (Coello & Delevoye-Turrell, 2007; Hunnius & Bekkering,
9 2014). Accordingly, proactive gaze movements have been shown to be facilitated in the
10 presence of information about the shape of the hand (Ambrosini et al., 2011) or when infants
11 possess sufficient motor expertise about a given action (Ambrosini et al., 2013; Geangu et al.,
12 2015). Attending the motor component of the action must then be required to understand the
13 goal of an actor.

14 Contrasting with this approach, some authors have highlighted the fact that decoding the goal
15 of the actor on the sole basis of the observed kinematics was possible only in rare cases of
16 unambiguous actions (Hunnius & Bekkering, 2014; Jacob & Jeannerod, 2005). Alternatively,
17 it has been proposed that kinematic processing would be guided by the prior activation of a
18 prediction of the actor's goal driven by contextual information (Kilner, Friston, & Frith, 2007)
19 or by non-motor components of the action, such as the object-tool (Bach, Nicholson, & Hudson,
20 2014). We will subsequently refer to these approaches as "predictive approaches". Accordingly,
21 it has been shown that prior knowledge about the actor's goal modifies the subsequent
22 processing of the kinematics by the observer (Hudson, Nicholson, Ellis, & Bach, 2016; Hudson,
23 Nicholson, Simpson, Ellis, & Bach, 2016). Similarly, it has been demonstrated that fMRI brain
24 activity during the processing of goals is more similar to the processing of object-tools than to
25 the processing of kinematics (Nicholson, Roser, & Bach, 2017). Goal processing may then rely

1 more on object-tool information than on information related to visual kinematics. Furthermore,
2 observers attend to information about trajectory to a greater extent for dropping than for placing
3 actions, suggesting that they differentially use kinematic information depending on the action
4 goal of the actor (Loucks & Pechey, 2016).

5 Together, the available evidence is not conclusive about whether action decoding is first driven
6 by the processing of the visual kinematics (e.g., the grip), or by the processing of non-motor
7 components (e.g., the object-tool) of the action, and to what extent action decoding is sensitive
8 to the availability of non-motor information about the action. Indeed, studies supporting
9 sensorimotor approaches tend to carry out experiments in which kinematics are the sole
10 discriminant information about the action, whereas predictive approaches tend to present
11 contextual information before the presentation of a target action. Consequently, although we
12 know that both kinematics and goal prediction are involved in action processing, whether action
13 processing is driven by the early decoding of visual kinematics or by a prediction about the
14 actor's goal through the processing of non-motor action components is still unclear. The overall
15 weight of goals in action decisions is not informative either, as visual kinematics may still be
16 processed first (see for example Kilner & Frith, 2008; Tidoni & Candidi, 2016). The
17 spontaneous orientation of visual attention towards visual kinematics or goal-related
18 information may help dissociating the two approaches. Visual attention has indeed been found
19 to impact the processes involved in the decoding of others' actions (D'Innocenzo, Gonzalez,
20 Nowicky, Williams, & Bishop, 2017; Donaldson, Gurvich, Fielding, & Enticott, 2015; Leonetti
21 et al., 2015; Muthukumaraswamy & Singh, 2008; Perry, Troje, & Bentin, 2010; Riach, Holmes,
22 Franklin, & Wright, 2018; Schuch, Bayliss, Klein, & Tipper, 2010; Woodruff & Klein, 2013;
23 Wright et al., 2018) and to be affected by visual kinematics and goal-related information
24 (Humphreys et al., 2013 for review). Yet the temporal dynamics of visual attention allocation
25 on visual kinematics and goal-related information remains to determine.

1 The present study aimed at investigating what captures attention first in an action discrimination
2 task where observers search for correct actions among distractor actions that could have either
3 the same grip or the same goal as the target action. The discrimination task is well-suited to
4 directly and independently oppose grip and goal dimensions. In other words, is visual attention
5 preferentially driven towards grip information or towards non-motor information that may help
6 building a prediction about the goal of the actor?

7 In the present study, we followed the repartition of eye movements during a visual search task
8 to evaluate the influence of grip and goal-related information (e.g. orientation of the object) on
9 the temporal allocation of visuospatial attention. Static photographs of actions were used, which
10 allow displaying both grip and goal information at the exact same time. Grip configuration may
11 not be as predictive of the outcome of the action as the full dynamic kinematics. However,
12 significant changes in grip configuration can still be very informative of whether an action is
13 correct or not overall. Moreover, static visual kinematics have been shown to be particularly
14 important to identify what an actor is doing with an object (Naish, Reader, Houston-Price,
15 Bremner, & Holmes, 2013). Therefore, visual kinematics have been manipulated through
16 changes in grip configuration in our stimuli. Participants were then asked to find a picture
17 displaying a typical object-directed action among distractor action pictures. Distractor pictures
18 displayed either a “similar action goal but a dissimilar grip”, or a “similar grip but a dissimilar
19 action goal”, or both a “dissimilar action goal and a dissimilar grip”. In case observers are first
20 paying attention towards the grip to derive the action goal, “similar grip but dissimilar action
21 goal” distractors should capture visual attention earlier than “similar action goal but dissimilar
22 grip” distractors. Alternatively, if observers first use non-motor information of the action to
23 orient the processing of kinematic information, then “similar action goal but dissimilar grip”
24 distractors should capture visual attention earlier than “similar grip but dissimilar action goal”.

25

1 **Methods**

2 **Participants**

3 Twenty-two participants took part in the study¹. Two participants were left-handed according
4 to the Edinburgh handedness inventory (EHI; Oldfield, 1971) and were then excluded. One
5 participant was excluded because of technical problems during the experimental session.
6 Finally, two participants were excluded because of an atypical pattern of fixation in comparison
7 to the remaining participants (see below). Eighteen participants (mean age 23, age range 18-27,
8 5 males) were then included in the final sample. All were right-handed (mean EHI 96%, from
9 63 to 100%), reported normal or corrected-to-normal vision. They provided written informed
10 consent and were not paid for their participation. The study followed the ethical guidelines of
11 the University of Lille and was in accordance with the declaration of Helsinki (1964, revised in
12 2013).

13 **Stimuli and Design**

14 Twenty objects were selected. For each object, four 512 × 341 pixel coloured photographs of
15 object-directed actions were designed by crossing the correctness of the grip and goal
16 components of the action: the object-directed action could display a “Correct Grip and Correct
17 Goal”, a “Correct Grip only”, a “Correct Goal only”, or both “Incorrect Grip and Incorrect
18 Goal”. Correct grips were defined as the typical grasp-to-use of the object. Incorrect grips then
19 corresponded to an atypical (but not impossible) grasp-to-use of the object. Similarly, goals
20 were considered correct if the typical function of the object could be achieved. Incorrect goals
21 then corresponded to an atypical (but not impossible) goal according to the main function of

¹ The sample size of about 20 participants was determined based on previous eye tracking studies using a similar paradigm (e.g. target search in 4-pictures display) in which differences of about 3% of fixation proportion were reported between two pictures in competition (e.g., Kalénine et al. 2012, Cohen *d* of 0.12 for the estimated difference of 3%). A power analysis indicated that twenty participants was sufficient to ensure a statistical power of 0.82 to detect difference in fixation proportion between two pictures (calculated from 50 simulations using the powerCurve function of the R package simr, Green & MacLeod, 2016).

1 the object. Importantly, the incorrect grip did not prevent the correct goal from being achieved.
2 For example, using a power grasp to write with an upright pencil is atypical but does not prevent
3 writing. On the contrary, using a precision grip to write with a pencil upside down does not
4 allow writing although the grip configuration applied on the pencil (the precision grip) is
5 typical. Thus, grip and goal varied independently from one another. An example of the stimuli
6 can be found in Figure 1. The full set of stimuli is available as supplementary materials.

7 [INSERT FIGURE 1 ABOUT HERE]

8 **Procedure**

9 Participants were comfortably seated in front of a 1024 x 768 computer screen in a quiet and
10 darkened room. Head movements were restrained with a chin and forehead rest to reduce
11 measurement errors. The vision was binocular but only the position of the left eye was recorded
12 for all participants. Eye movements were measured continuously with an infrared video-based
13 eye tracking system (EyeLink, SR Research), sampled at 500 Hz. Before each experimental
14 session, the eye tracker was calibrated by asking participants to fixate a set of 9 fixed locations
15 distributed across the screen. After the calibration, instructions were given to each participant
16 and a training session with feedback was provided. The training session included five
17 representative trials with objects that were not in the experimental session. The experimental
18 session was similar to the practice session, but without feedback. Each trial began with a
19 fixation cross in the center on the screen. Participants had to click on the fixation cross to make
20 the display appear. For each reference object, pictures were randomly assigned to the different
21 corners of the screen. The centre of each picture was at 13 degree of visual angle of the centre
22 of the screen. Participants were asked to click on the picture displaying the correct action
23 according to the typical use of the object with the mouse. The “Correct Grip and Correct Goal”
24 picture was defined as the “Target”, the “Correct Grip only” picture as the “Grip-distractor”,
25 the “Correct Goal only” picture as the “Goal-distractor”, and the “Incorrect Grip and Incorrect

1 Goal” picture as the “Unrelated-distractor”. Overall, there were 20 trials corresponding to each
2 reference object. Eye movements were recorded from the beginning of each trial until the
3 mouse-click response on the images.

4 **Fixation proportion**

5 Data analysis followed a procedure previously used in eye tracking studies to capture the
6 evolution of eye movement distribution across time (Kalénine, Mirman, Middleton, &
7 Buxbaum, 2012; Lee, Middleton, Mirman, Kalénine, & Buxbaum, 2013; Lee, Mirman, &
8 Buxbaum, 2014; Mirman, Dixon, & Magnuson, 2008; Mirman & Magnuson, 2009). Four areas
9 of interest (AOI) associated with the displayed pictures were defined as the four 512 x 341 pixel
10 quadrants of the 1024 x 643 pixel computer screen. We considered that participants fixated a
11 given action type (“Target”, “Grip-distractor”, “Goal-distractor” and “Unrelated-distractor”)
12 when their gaze fell into the corresponding AOI. Fixation proportion on each action type was
13 calculated over 50 ms time bins in order to reduce the noise in the fixation estimates and to
14 facilitate statistical model fitting (see Data analysis section). For each time bin of each
15 participant or each item, mean fixation proportion for each action type was computed by
16 dividing the number of fixations on this action type by the total number of trials to avoid the
17 selection bias introduced by varying trial-termination times (cf. Kukona, Fang, Aicher, Chen,
18 & Magnuson, 2011; Mirman & Magnuson, 2009; Mirman, Strauss, Dixon, & Magnuson, 2009).

19 **Saliency Maps**

20 The experiment aimed at assessing which action component first drives visual attention when
21 identifying a target action among distractors. Yet visual selective attention is largely influenced
22 by the visual properties of the image to explore (e.g., colour, spatial orientation, intensity etc.).
23 In order to partial out the effect of possible differences in low-level visual features between the
24 four images on gaze behaviour during target action visual search, saliency maps were computed
25 with the Saliency ToolBox for each stimuli (Walther & Koch, 2006). Saliency values were then

1 extracted for each pixel and averaged across each area of interest (see “Fixation proportion”
2 section). A saliency index was therefore available for each of the four pictures (“Target”, “Grip-
3 distractor”, “Goal-distractor”, “Unrelated-distractor”) of each of the 20 displays. Paired
4 comparisons showed a perceptual advantage for the “Goal-distractor” over the “Grip-
5 distractor” ($t_{19} = -5$, $p < .001$). Saliency indices were thus added as covariate in a
6 complementary by-item analysis.

7 **Data Analysis**

8 The temporal dynamics of fixations on the two “Grip-“ and “Goal-distractor” pictures were
9 compared in order to determine whether visual attention is first captured by grip or by goal
10 information². To capture the effect of time, fixation proportions over time were fitted as a
11 function of fourth-order orthogonal polynomials. Orthogonal polynomials are well suited to
12 characterize different behaviours of the fixation curves (see Mirman, 2014 for an introduction
13 to Growth Curve Analysis). Fourth order polynomials were chosen since they have been proven
14 successful to capture the rise and fall of the fixation curves of competing distractors during
15 target identification (Mirman, 2014; Mirman et al., 2008). The intercept reflects differences in
16 the overall height of the curve between conditions. In the present study intercept differences
17 between goal and grip distractors would not inform on which action dimension is processed
18 first and was not of primary interest. Differences in timing between grip and goal processing
19 would be particularly reflected by differences on the linear (1st order) and/or on the cubic (3rd
20 order) time terms (Kalénine et al., 2012; Lee et al., 2013). If visual attention is first captured by
21 grip information, then we should observe earlier fixations on the “Grip-distractor” in
22 comparison to the “Goal-distractor”. This would be reflected by a more negative linear estimate
23 (slope) or cubic estimate for the goal compared to the grip fixation curve. Conversely, we

² As the target fixation curve was incomparable to distractor fixation curves, the target was not included in the analysis (see Figure 2). The unrelated distractor was not added in the analysis because it has no influence on the test of our main hypothesis while increasing model complexity.

1 should observe earlier fixations on the “Goal-distractor” compared to the “Grip-distractor” if
 2 visual attention is first captured by goal information. This would be reflected by a more positive
 3 linear estimate or cubic estimate for the goal compared to the grip fixation curve. For example,
 4 the cubic time term has been shown to be sensitive to differences in the early and late inflexions
 5 of the fixation curves (see Figure 3 of Kalénine et al., 2012 for an illustration). An early increase
 6 of fixation proportion on the “Goal-distractor” in comparison to the “Grip-distractor” would
 7 thus be statistically reflected by an interaction between the variable “distractor type” and the
 8 cubic (3rd polynomial order) time term.

9 In the main analysis, fixation proportions on the distractor pictures were averaged over items
 10 and analysed as a function of the fixed-effect factors of time (fourth-order orthogonal
 11 polynomials), distractor type (“Grip-distractor”, “Goal-distractor”) and the interaction between
 12 the two factors. The random structure includes random slopes for participants on each time
 13 term³. In a complementary analysis, fixation proportions on the distractor pictures were
 14 averaged over subjects and analysed as a function of the fixed-effect factors of time, distractor
 15 type, their interaction, and image saliency index and its interaction with time. By adding the
 16 saliency index covariate to the model, this complementary by-item analysis aimed at partialling
 17 out the influence of low-level visual features on the fixation curves. The random structure
 18 includes random slopes for items on each time term⁴. Mixed-effect models of fixation
 19 proportions were then fitted with REML using the `lmer` function from the *lme4 1.1-17* package
 20 (Bates, Mächler, Bolker, & Walker, 2015) in R version 3.4.4.

21 Overall main effects and interactions were evaluated with F statistics using the `anova` function
 22 of the *lmerTest 3.0-1* package (Kuznetsova, Brockhoff, & Christensen, 2017). The degrees of

³ The R syntax of the model was: Fixation proportion = (intercept + linear + quadratic + cubic + quartic) * distractor type + (intercept + linear + quadratic + cubic + quartic | participant : distractor type)

⁴ The R syntax of the model was: Fixation proportion = (intercept + linear + quadratic + cubic + quartic) * distractor type + (intercept + linear + quadratic + cubic + quartic) * saliency index (intercept + linear + quadratic + cubic + quartic | participant : distractor type)

1 freedom of the denominator were approximated with the Satterthwaite's method. This method
2 produces acceptable type 1 error rates (Luke, 2017). T-Tests on individual parameter estimates
3 were then used to evaluate the contrasts of interest between distractors.

4 **Results**

5 **Main analysis of fixation proportions**

6 Overall, only trials on which the target image was correctly identified were included in the
7 fixation analyses (mean accuracy 91% +/- 28%). As the task was to find the target action, two
8 participants for whom fixations on the target never reached at least 50% of all fixations were
9 considered performing the task correctly but with an atypical visual strategy and were excluded
10 from the analysis. After visual inspection, the time-window of analysis was selected from
11 display onset to 1500ms after display onset, when the averaged target fixation curve reached a
12 first plateau (see Figure 2 and Lee et al., 2013; Mirman et al., 2008 for similar procedure).

13
14 The analysis showed no main effect of distractor type ($F_{1,34} = 0.45$, $p = .506$). This indicates
15 that overall, grip and goal distractors received an equivalent proportion of fixations over the
16 whole 1500 ms time window ("Grip-distractor" mean proportion 0.21; "Goal-distractor" mean
17 proportion 0.22). Importantly, however, a significant interaction was found between distractor
18 type and the cubic (3rd order) time-term ($F_{1,34} = 4.77$, $p = .041$), reflecting an influence of
19 distractor type on the time course of fixation proportion. The distractor type x cubic time term
20 interaction was driven by an earlier increase of fixation proportion over the "Goal-distractor"
21 in comparison to the "Grip-distractor" (estimate = - 0.13, SE = 0.06), as visible on Figure 2.
22 Distractor type did not interact with any other time terms (all $p > .157$).

23

24 **Complementary analysis of fixation proportions with saliency index as covariate**

1 In the complementary by-item analysis including the saliency index, the interaction between
2 distractor type and the cubic (3rd order) time-term was marginally significant ($F_{1,37} = 3.76$, $p =$
3 $.060$) after taking the saliency index into account. As previously observed, there was an earlier
4 rise in fixation proportion over the “Goal-distractor” in comparison to the “Grip-distractor”
5 (estimate = - 0.13, SE = 0.06). Importantly, there were no effects involving the saliency index
6 on fixation proportions, neither in isolation (main effect $F_{1,37} = 0.15$, $p = .706$), nor in interaction
7 with the different time terms (all $p > .477$). In addition, at the item level, no correlations were
8 found between the amplitude of grip and goal processing early in the time window (extracted
9 from the random cubic estimates for items) and the saliency index (“Grip-distractor” condition:
10 $r = 0.37$, $p = .107$; “Goal-distractor” condition: $r = -0.2$, $p = .399$). Overall, the complementary
11 analysis indicates that we can be confident that the earlier fixations on goal-distractors cannot
12 be fully explained by the greater visual saliency of the images in this condition.

13 [INSERT FIGURE 2 ABOUT HERE]

14 Discussion

15 The present study aimed at investigating the spontaneous capture of visual attention by grip and
16 goal information. More specifically, we wanted to determine whether visual attention would be
17 preferentially driven towards grip-related or goal-related information. In a visual search task,
18 participants were asked to explore and select the photograph displaying the correct tool use
19 action among action distractors. Gaze movements were used to evaluate to what extent grip-
20 related (same grip as the target, but with a different action goal) and goal-related (same goal as
21 the target but involving a different grip) distractors would capture participants’ visual attention
22 before the identification of the target. Visual attention was found preferentially captured by
23 goal-related distractors in comparison to grip-related distractors, but in a time-dependent
24 manner. Visual attention over the goal-related distractors increased in the first part of the visual
25 exploration but decreased in the second part. Thus, observers do not only use goal-related

1 information overall when decoding others' actions, they rely on it first. They disengage their
2 attention from it afterwards to use the other available information.

3 The importance of goals in action processing has been highlighted in several theoretical models
4 (Bach et al., 2014; Cooper et al., 2014; van Elk et al., 2014) and is supported by many
5 experimental arguments (Flanagan et al., 2013; Nicholson et al., 2017; van Elk, Van Schie, &
6 Bekkering, 2008). Predictive approaches go a step further by suggesting that a prediction about
7 others' goals is first needed to make sense of their actual movement kinematics (Kilner, 2011;
8 Kilner et al., 2007). Yet the greater weight of goal information in action decoding is not
9 sufficient to support the "goal first processing" hypothesis, since strong activation of goal
10 information could be derived from the first analysis of visual kinematics (Kilner & Frith, 2008;
11 Tidoni & Candidi, 2016). Data about the time course of processing of grip and goal information
12 are thus particularly needed to directly evaluate predictive approaches of action understanding
13 (Catmur, 2015). The "goal first processing" hypothesis has been indirectly supported by EEG
14 studies showing an early modulation of brain activity as a function of the goals of observed
15 actions (Ortigue, Thompson, Parasuraman, & Grafton, 2009). In a recent behavioural study,
16 we reported more direct evidence in favour of the "goal first" hypothesis. The recognition of
17 visual actions was facilitated after being briefly primed (66 ms) by actions showing the same
18 action goal but not the same action grip (Decroix & Kalénine, 2018). This result demonstrated
19 that goal-related information is used earlier than information about visual kinematics when the
20 task puts minimal requirement on the visuo-attentional system (i.e. central presentation of one
21 action picture at a time). In the present study, we further show that very early in the action
22 recognition process, goal-related information is favoured over visual kinematics when the two
23 dimensions are competing for attention (i.e. visual search of the correct actions). This suggests
24 that the predictive mechanisms at play in action decoding interact with attentional processes in
25 the determination of the temporal dynamics of action processing.

1 Although the gaze pattern corroborates the “goal first processing” hypothesis, visual attention
2 during the action discrimination task was not solely captured by correct goal-related
3 information but was also influenced by correct kinematic information. The disengagement of
4 visual attention from the goal-related distractor in the second part of the visual exploration
5 provides further evidence for the use of visual kinematics during action recognition. Visual
6 kinematics are indeed known to provide sufficient information to discriminate between two
7 different goals (Cavallo, Koul, Ansuini, Capozzi, & Becchio, 2016), and observers are able to
8 use such information to anticipate the actor’s goal (Ansuini et al., 2014; Fischer, Prinz, & Lotz,
9 2008; Lewkowicz, Quesque, Coello, & Delevoye-Turrell, 2015). Visual kinematics are thus
10 relevant features for understanding the actor’s goal. Predictive approaches suggest that visual
11 kinematics are used to test the goal prediction that has been derived from non-motor related
12 information (Donnarumma, Costantini, Ambrosini, Friston, & Pezzulo, 2017; Kilner, 2011;
13 Kilner et al., 2007). Converging evidence suggests that visual kinematics are used to update
14 predictions about the actor’s action goal. Motor simulation has been shown to reflect *expected*
15 visual kinematics during the first steps of action observation but *actual* visual kinematics during
16 the last steps of action observation (Cavallo, Buccioni, Castiello, & Becchio, 2013). Recently,
17 Koul, Soriano, Tversky, Becchio and Cavallo (2019) further showed that actual visual
18 kinematics are used to update the on-going motor simulation as a function of their
19 informativeness. Accordingly, the overall pattern of fixations reported here supports predictive
20 approaches of action recognition, as visual kinematics became more relevant than goal-related
21 information in the second part of the visual exploration.

22 In our experiment, information about the object is required to perform the task (search for the
23 correct action according to the typical use of the object) and goal correctness is manipulated by
24 changing the orientation of the object (e.g., pen upside down). It is then possible that the early
25 capture of visual attention by goal-related information has been biased by task demands, which

1 orient towards object processing. When looking for the correct action without more instructions,
2 participants may have primarily searched for object information. As the object was present in
3 each condition, the mere presence of the object could not have favoured one type of distractor
4 over another. However, one may wonder whether visual attention might have been primarily
5 drawn towards distractor objects presented in the same correct orientation as the target, which
6 would have favoured distractors sharing the same correct action goal. Yet it is unclear whether
7 the modification of object orientation has changed object familiarity and/or recognition. Indeed,
8 many object exemplars were simply mirror-reversed according to the vertical axis, which makes
9 the presentation of objects in actions containing goal-violations equally visually familiar despite
10 inappropriate for right-handed use (see supplementary materials). In addition, goal priority was
11 confirmed in the by-item analysis that accounts for the possible heterogeneity in the stimulus
12 set. Therefore, we believe that it is relatively unlikely that the present pattern of results can be
13 fully explained by our manipulation of goal information. An interesting direction for future
14 studies would be to dissociate object function (that provides information about the typical goal
15 of the action) and object identity. The same object with alternative functions (e.g., pour or drink
16 from recipient) or two different objects with the same possible function (e.g., meat-knife or
17 box-cutter to cut) could be used for this purpose, although an independent manipulation of the
18 corresponding use gestures might be challenging. Regardless, the role of object identity in
19 deriving goal-related information requires deeper understanding.

20 Although many important theoretical accounts have suggested a key role of object information
21 in deriving predictions about the actors' goal during action decoding (Bach et al., 2014; van Elk
22 et al., 2014), several authors have discussed the scope of such accounts (see for example
23 commentaries of Hommel, 2014; Uithol & Maranesi, 2014). In particular, it remains to
24 determine whether other types of (non-object directed) actions are still processed in a predictive
25 manner. Some results suggest that it is indeed the case (Bach & Schenke, 2017). For example,

1 Manera, Becchio, Schouten, Bara and Verfaillie (2011) found that the communicative actions
2 of one actor could be used as pieces of information to predict the actions of another actor, even
3 though there was no direct contact between the two actors. If so, goal-priority during action
4 processing may not be the privilege of object-directed actions. Nevertheless, we believe that
5 the role of kinematics versus goal-related information in action decoding can be sensitive to
6 attentional and situational factors. Goal-priority may be nuanced in certain situations. Some
7 results indeed suggest that it may be possible to modify the way actions are spontaneously
8 processed. For example, Pomiechowska and Csibra (2017) found that perception of object-
9 directed actions did not induce mu suppression (i.e., a neurophysiological marker of
10 sensorimotor cortex activity) when actions were preceded by speech, in comparison to the
11 perception of actions in absence of speech. Future studies should then determine whether task
12 demands and situation could bias the spontaneous orientation of visual attention towards
13 kinematics versus goal-related information during the observation of object-directed actions.
14 Overall, the present study indicates that the visuo-attentional system is first influenced by goal-
15 related information when searching for the correct action among distractors. Although results
16 provide direct support for predictive approaches of action understanding, they might also be
17 incorporated into a broader theoretical framework in which task demands could flexibly bias
18 visual attention towards visual kinematics or non-motor action-related information.

19

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23 saliency maps.

24 **Open Practices Statements:** The experiment reported here was not preregistered. Data are
25 available at <https://osf.io/ejtay/>. The full set of stimuli is available as supplementary materials.

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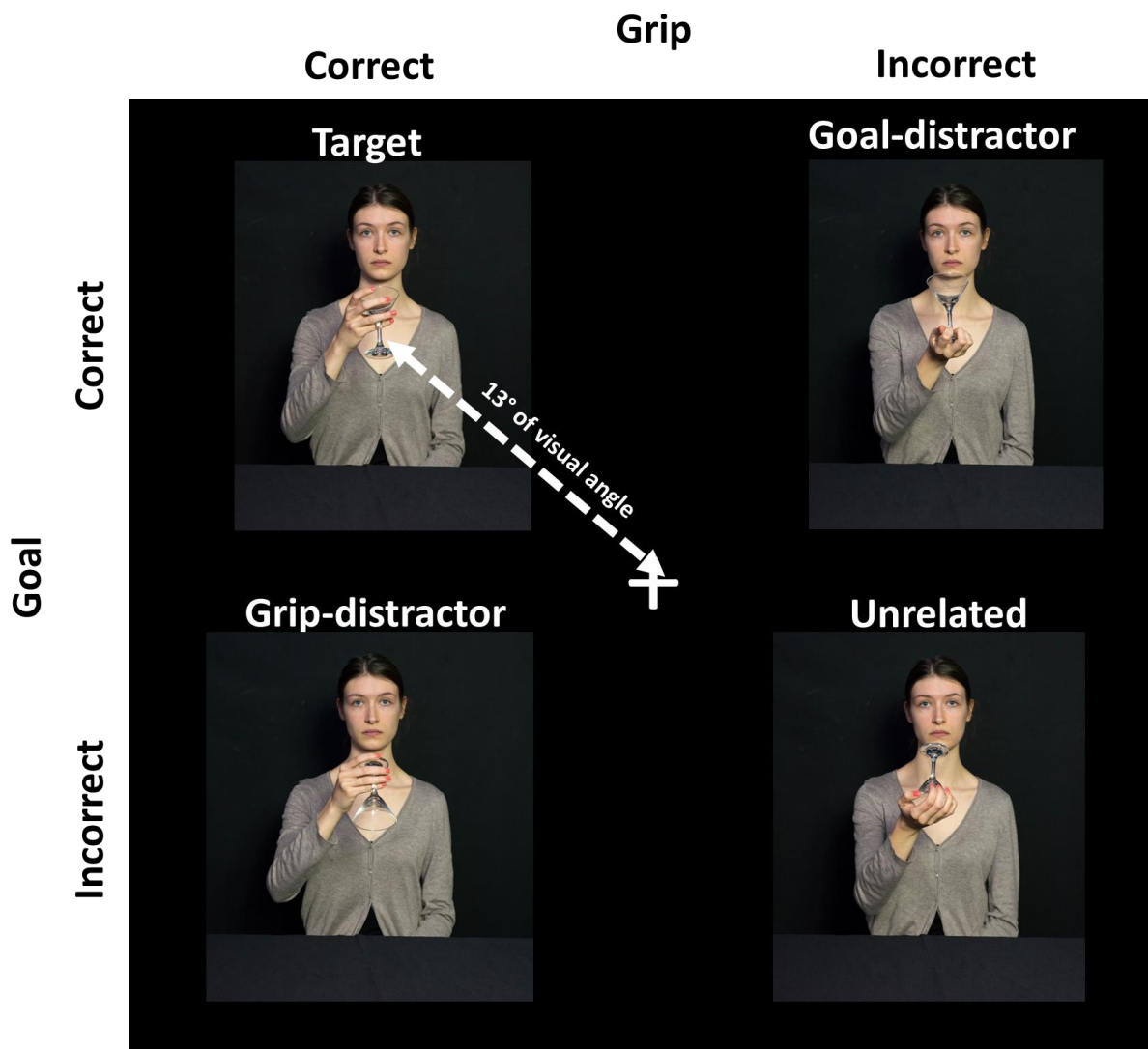
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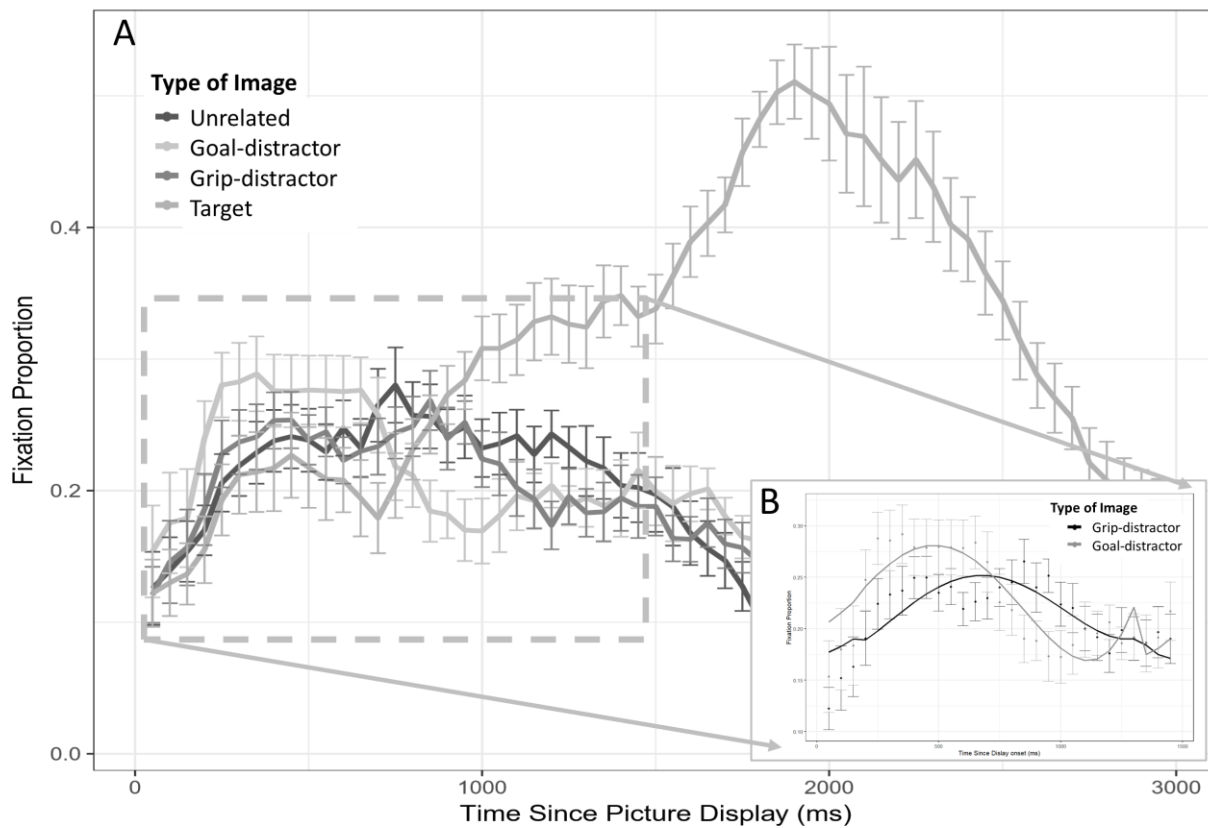
1 **Figure 1.** Design of the experiment.

2 **Figure 2.** Mean fixation proportion and standard errors (error bars) over time as a function of
3 image condition (A) and model fit of the data for the Grip-distractor and Goal-distractor (B)

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